SHOCK TUBE DESIGN

A Senior Scholars Thesis

by

PETER KYLE KOPPENBERGER

Submitted to the Office of Undergraduate Research
Texas A&M University
in partial fulfillment of the requirements for the designation as

UNDERGRADUATE RESEARCH SCHOLAR

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Approved by:

Research Advisor:	Devesh Ranjan
Associate Dean for Undergraduate Research:	Robert C. Webb

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ABSTRACT

Shock Tube Design. (April 2010)

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Shock accelerated flows exhibit some of the most violent and complex mechanisms in nature by which two separate fluids can be mixed. The Richtmyer-Meshkov instability (RMI) is generated when a perturbed interface between two fluids is impulsively accelerated by a shock wave. In order to further study the phenomenon of the RMI, a new shock tube will be designed. This shock tube will have the capability to change the angle of inclination, allowing for a diverse possibility of fluid interfaces, and provide two driver sections to allow for dual shock capability. The tube was designed to accommodate a 2.5 MACH shockwave, and incorporated a factor of safety of 3 in the design. A modular approach to design was followed to allow further diversification of the shock tube by changing the configuration of the modules. A circular driver section was used to maximize volume and a square driven section was used to minimize affects from the boundary layer. A slide rail mechanism was devised for changing the diaphragms which allows a single person to change the diaphragm in a timely manner. The entire tube is supported on an I-beam to maintain the rigidity of the system while inclined. To accommodate a variable inclination, a hybrid winch support system was designed. A winch changes the angle of the tube and a telescoping support system maintains the position during experimentation. It was determined after running

COSMOS finite element stress analysis, that with the 2.5 MPa internal pressure associated with a 2.5 MACH shock wave, a 19.05 mm sidewall thickness was needed to provide a factor of safety of 3.

DEDICATION

I dedicate this paper and research to my parents. Without their support, both monetarily and spiritually, I would be lost and without this opportunity.

ACKNOWLEDGMENTS

I thank Dr. Devesh Ranjan for being my mentor, advisor, and friend; without him I would not have had the opportunity to do my research or become a scholar. I thank my parents and sister for their relentless support and all my other family members that always stand behind me. I thank Jacob McFarland for being a good friend and for helping me with my research and writing this paper. I also thank Sarat Kuchibhatla for being a good friend and for helping me with my research and writing this paper.

NOMENCLATURE

FEA	Finite Element Analysis
FOS	Factor Of Safety
KHI	Kelvin-Helmholtz Instability
RMI	Richtmyer-Meshkov Instability
RTI	Raleigh-Taylor Instability
2D	Two Dimensional
3D	Three Dimensional

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CHAPTER I

INTRODUCTION

The way fluid interactions develop over time is of large importance to the scientific community. In Inertial Confinement Fusion, supernovas, weather, supersonic engines, and nuclear explosions, predicting patterns is based on the use of advanced computer models. Further studying instabilities will allow more precise and accurate predictions of the dynamics of fluid interactions. Enhancing the knowledge and predictability of these instabilities will ultimately allow engineers to better understand and control turbulence.

Instabilities

Two fluid instabilities are the Raleigh-Taylor Instability (RTI), and the Richtmyer-Meshkov Instability (RMI). RT instabilities are formed when a fluid of higher density rests above a fluid of lower density relative to the direction of acceleration. In the real world, no fluid interface is free of perturbations, and these perturbations represent local density gradient misalignments, driving mixing. In a perfect interface with no perturbations, there would be no perturbation growth and thus, no mixing. These instabilities grow due to the lighter fluid's tendency to rise into the heavier fluid, namely buoyancy. The RMI can be seen as the impulsive limit of the RTI. The RMI is seen

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This thesis follows the style of *Journal of the Fluid Mechanics.*

when two fluids with different densities are exposed to a impulse acceleration, or shock, and initial perturbations on the interface of those two fluids are amplified over time. The driving mechanism for this amplification is the baroclinic vorticity generated by the misalignment of the pressure gradient between the shock wave and initial perturbations in the interface (Brouillette 2003). As instabilities grow and become more distorted, secondary instabilities, such as the Kelvin-Helmholtz Instability (KHI), become the drivers for turbulence growth and mixing. Shearing between two fluids causes the KHI, and can be seen in the later stages of the RTI and RMI.

RMI

The focus of this paper will be towards RMI, and more in particular, building an experimental apparatus to study this phenomenon. The RMI is currently the focus of much research due to its role in inertial confinement fusion. In ICF, the RMI causes mixing between the capsule material and the fuel within, limiting final compression and thus the ability to achieve energy break-even or production (Brouillette 2003). It has become clear that the evolution of supernovae is dependent on the formation of the RMI (Drake *et al*. 2009). This implies that Richtmyer-Meshkov instabilities are the driving phenomenon in the development of the universe. In order to better understand and address these problems, it is critical to thoroughly understand and have the ability to predict the development of the RMI. Although computational models have agreed with experimental data for 2D single-mode cases at early times of growth, there is a need for more experimental data to support computational 2D, 3D, and multi-mode models over both early time growth and late time decay into turbulence (Krivets *et al.* 2007). For these and other reasons, it can be seen that manufacturing a facility to further the knowledge of these instabilities is important.

Apparatuses

To design a facility for testing the RMI, existing facilities were reviewed initially. By doing so, the knowledge gained from previous facilities will be incorporated into the design of this facility. There are several ways to produce conditions necessary for the creation of the RMI, and each method requires three essentials. An impulsive acceleration is needed to drive the instabilities; an interface of two fluids with specific initial conditions is needed; and a diagnostic system is needed to observe and measure the fluid interactions. Determining a diagnostics setup for a system is unique to the system's configuration and will be discussed in the instrumentation section later. In creating an impulsive acceleration, many different methods have been used. Dimonte used an electric linear motor to impulsively accelerate a free-moving test section which contained a fluid interface (Brouillette 2003). Jacobs & Sheeley also used a free-moving test section, containing a fluid interface, that impacted a spring after free falling under the prescience of gravity (Brouillette 2003). Using a stationary test section and imparting a shock wave onto an interface is a well-liked method seen in the shock tube. The shock is usually generated by the rapid release of high-pressure gas, but can also be done with explosives or laser radiation.

Shock tube

A shock wave that intersects a fluid interface will invoke the formation of the RMI. Since the test section is stationary, multiple initial conditions can be produced, making the shock tube a versatile and desirable choice for studying RMI. In a free-moving test section, the fluid interface is subject to changes in inertial forces during movement, limiting the ability to make complex initial conditions. Also, a stationary test section will allow a simpler diagnostic system. This paper will be a discussion on the design of a shock tube, focused on a test section that can produce various replicable initial conditions on a fluid interface.

CHAPTER II

METHODS

In the design process used for this project, several steps were taken to assure that the shock tube met Dr. Ranjan's criterion. The initial step was identifying certain specifications; each specification was looked at the component level initially and then at the system level. By focusing on the specifications individually, several solutions were devised to accomplish each, allowing for an open design that was not limited by any certain action. After several solutions were devised, all solutions to each problem were focused on simultaneously, where overlapps and conflicts in the system could be spotted. In other instances, it was seen that some solutions could be combined to facilitate a simpler design and save on costs and time. Part of the initial problem solving steps involved hand sketches, which also aided in communicating design ideas to other engineers and during brainstorming sessions.

After compiling initial designs for the components of the tubes, SolidWorks® was used to create 3D computer models, which allowed for easy manipulation of the design. In several instances, the designs were changed due to costs, manufacturability and feasibility, among other things. Using SolidWorks® allowed stress analysis of the designed components, both individually and in assembly. After conducting stress analysis on the components using COSMOS, each component was redesigned until all specifications were met. Approval from both Dr. Devesh Ranjan and a licensed

Professional Engineer is the final step in the design process. After approval, the design will be complete and ready for manufacturing.

Specifications

Specifications were given governing the design of this shock tube. The purpose of these requirements is to allow the shock tube to be diverse and have multi-utility. The diversity of this shock tube means it can facilitate many initial conditions, the most significant variable in RMI studies.

1. Dual driver sections
2. Variable Inclination
3. Square Cross-section
4. Modular construction
5. 2.5 MPa internal pressure rating
6. Factor of Safety of 3
7. Diagnostics accessibility
8. Ease of operation
9. $100k budget

Table 1. Design requirements for the shock tube specified by Dr. Devesh Ranjan.

Facilitating two driver sections in the shock tube allows the initial conditions to be subjected to two different shocks within short time periods, on the scale of microseconds. This allows the study of initial condition growth. Having the ability to alter the angle of the shock tube allows the shockwave to impact the fluid interface at various angles. The majority of preexisting shock tubes are fixed in a horizontal or vertical position, limiting the manipulability of the initial conditions. A square cross-section limits the effects of the boundary layer on the internal walls of the tube. This results in better experimental data. Modular construction has several benefits, one of them being more effective transportability. Since the tube will be constructed off-site, it will have to be shipped to the final location; shipping smaller pieces will be more cost effective and easier to find a shipping company. Another benefit of modularity is decreased manufacturing cost. Also, a modular design will allow the test section's location to be moved along the tube, allowing the user to change the time at which the reflected shockwave impacts the initial condition interface. The modular design means the test section can also be changed in the future for different experimental setups. An allowable internal pressure of 2.5 MPa gives the user the ability to create shockwaves up to Mach 3. The designated Factor of Safety gives the user a safe working environment while running experiments, and also gives some leeway for errors in the design, materials, and manufacturing process. Diagnostics are a crucial part in studying the RMI. It is important to have the ability to fully view the fluid interface before and during the shockwave impact.   Allowing adequate accessibility for the diagnostics systems will give the user the ability to gather superior data for analysis. Once up and running, the shock tube facility will need to be easy to operate. This means that during a certain experimental setup, diaphragms should be easy to replace, requiring only one person, and should be done in a timely matter. Each time an experiment is run, a new diaphragm will need to be inserted. The quicker this can be accomplished, the quicker experiments can be completed and the number of experiments can be increased. An increase in data will allow proper statistical analysis of the experimental data and ultimately improve the efficiency of experiments. The cost of materials and manufacturing for the shock tube is limited to $100,000. This budget does not include shipping, on site manipulations, or installation.

CHAPTER III

RESULTS

Shock tube

The completed shock tube consists of three main parts, namely, the driver section, the driven section, and the test section. The driver section drives the shock-front because of high pressured driving fluid contained in it. It contains the diaphragm holders, and the mechanisms that control their rupture along with an end cap. The driven section is the portion of the tube where the shock becomes uniform before encountering the fluid interface. The test section contains the diagnostics system and the initial condition manipulator. All three of these portions must be joined with airtight seals and must be able to withstand the internal pressure of the tube without failing. This whole shock tube structure must also be supported to eliminate excess deflection and allow for support during angular movement between 0 and 90 degrees.

Driver section

As the shock tube is designed for generating two shocks, two driver sections with two diaphragms are required. The two driver sections are located coaxially and butt against each other. The driver sections are to be circular in cross section to increase the internal volume and to withstand higher pressures. The driver sections named driver-1 and driver-2 are shown in Figure 1.

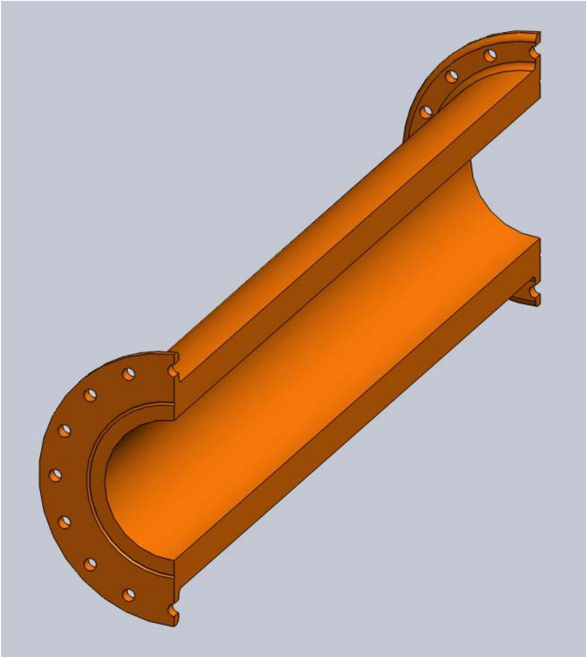

Figure 1. Section view of the driver section.

The end cap on the rear driver section is made of thicker material than the side walls because of its flat nature meant for mounting various probes and devices. If made semi-hemispherical or hemispherical the thickness could be decreased. The diaphragms must be held in place during experimentation and be easily replaceable between experiments. Two separate diaphragm holders were designed to accommodate these needs, one for the diaphragm between the two driver sections, diaphragm-1 and another for the diaphragm between the circular front driver section and the square driven section, diaphragm-2. The corresponding diaphragm holders are named diaphragm holder-1 and diaphragm holder-2. These two holders are shown in Figures 2 and 3.

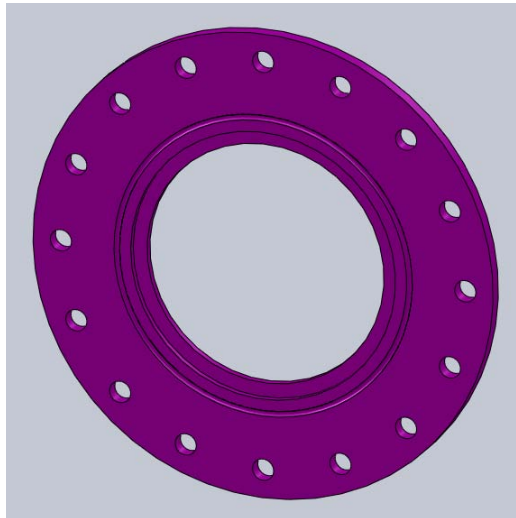

Figure 2. Diaphragm holder for the diaphragm between the two driver sections.

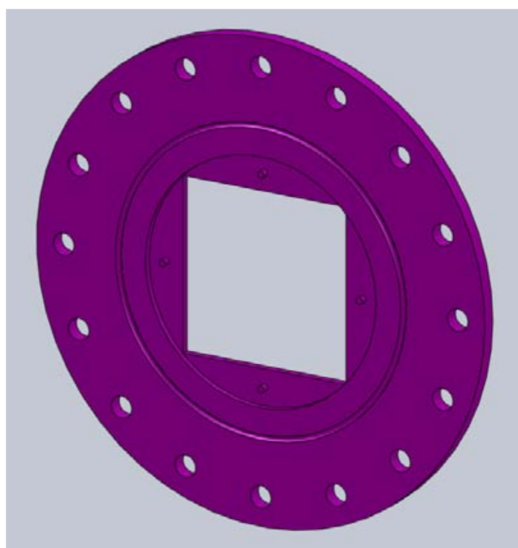

Figure 3. Diaphragm holder for the diaphragm between the driver2 and driven section.

Small protruding pins were incorporated into the second holder to hold the diaphragm in place and prevent unwanted rotation and slippage. Diaphragm-1 did not need pins to hold it in place because its angular position does not affect the shock. In order to accomplish the requirement of easily changeable by a single person, a system was designed consisting of a slider rod, tracks, and wheels along with a stop to prevent excessive movement. This system is shown in Figure 4.

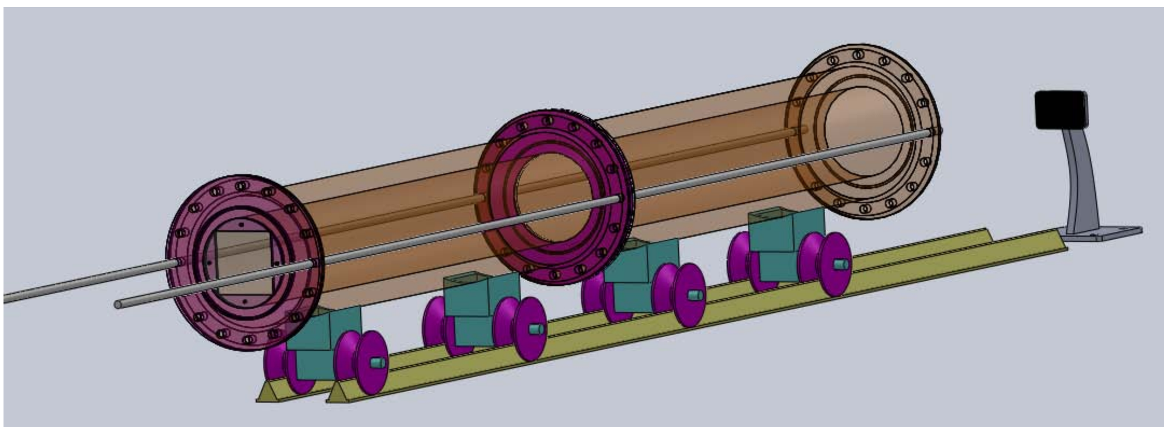

Figure 4. Rail system for changing the diaphragms.

The stop prevents the driver section from falling off the rail system. This system allows the user to unbolt the driver section flanges and slide back the driver sections to reveal the diaphragm, which can then be changed. A winch is located behind the stop and attaches to the cover on the back of the driver section. To change diaphragm-2, the front flange is unbolted, the winch is initiated, and the two driver sections are pulled away from the driven section, exposing diaphragm-2, which can then be replaced. To change the diaphragm-1, the driver-2 is replaced, the front flange is bolted and driver-1 flange is unbolted, the winch pulls driver-1 away and the diaphragm-1 can be replaced. If the user wants to limit the experiment to one shock, a solid plate can be switched out in the place of diaphragm holder-1. This plate can be seen in Figure 5 and doubles as the cap for the rear driver section.

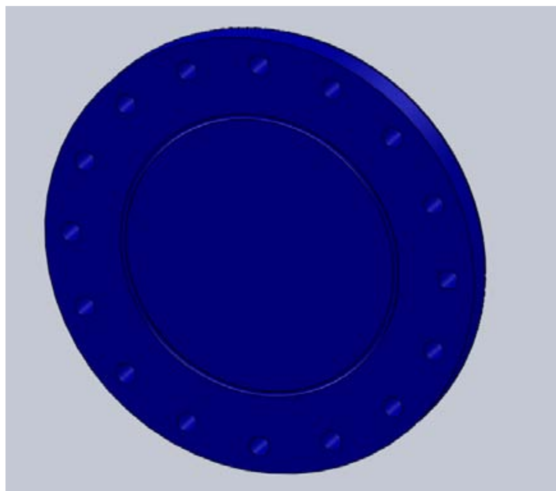

Figure 5. Plate that allows for single shock experiments and doubles as the rear driver section cap.

Driven section

The driven section is the portion of the tube that the shock travels down before reaching the fluid interface; it also stabilizes the shock wave allowing it to become planar. This section should not be too long, as this will cause unwanted boundary layer affects and loss of shock strength; it must not be too short, as this will not let the shockwave become uniform and planar. The inside walls need to be smooth, on the order of 20 RMS surface finish in order to prevent extraneous boundary layer interference. The complete driven section has 7 modular sections, five that are identical, one test section, and one that connects to the driver section, called the intermediate section. All the driven sections can be seen in Figures 6, 7, and 8, and Figure 9 shows an assembly of the driven sections.

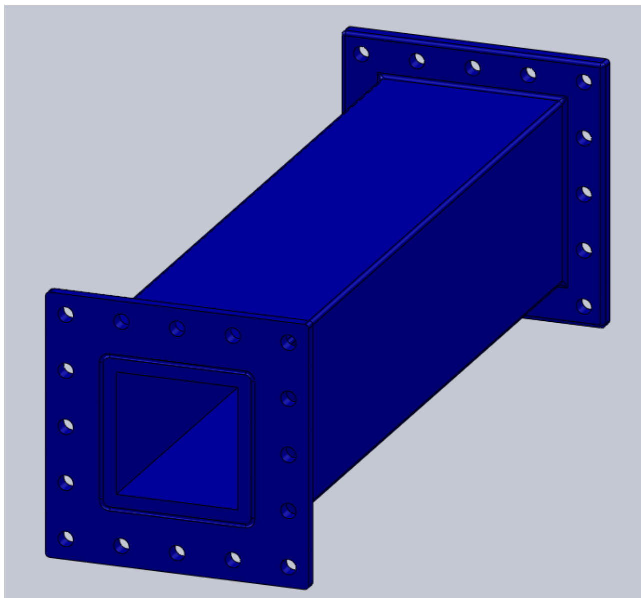

Figure 6. One of the five identical driven sections.

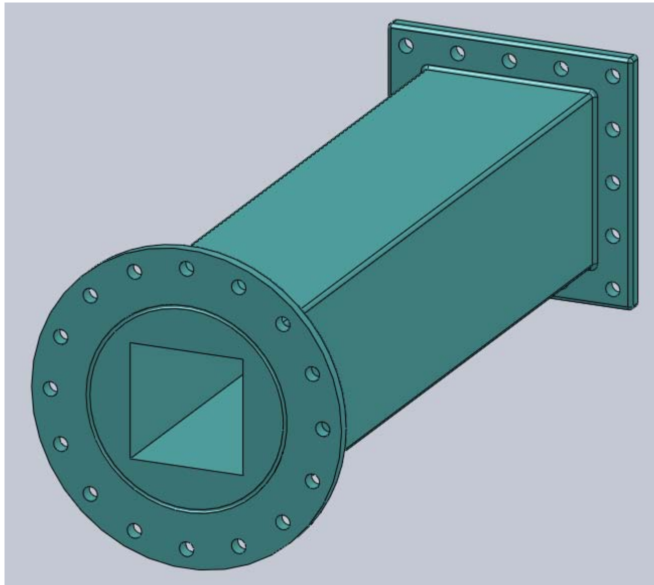

Figure 7. The intermediate section.

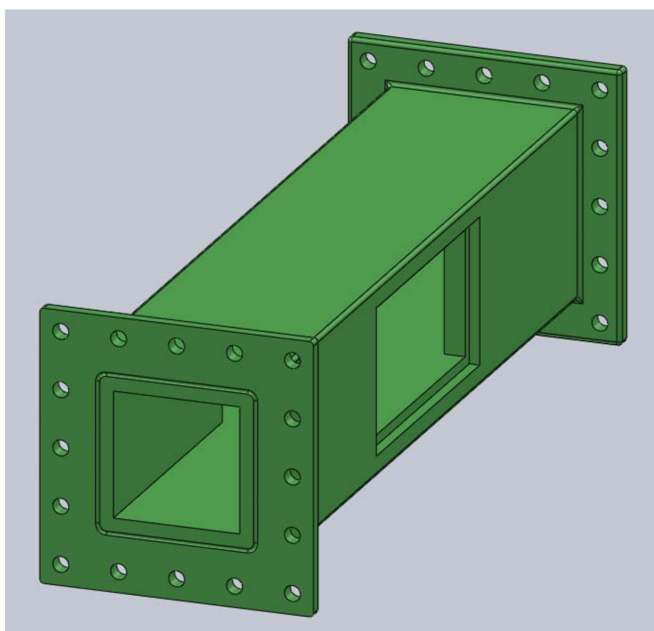

Figure 8. Incomplete test section.

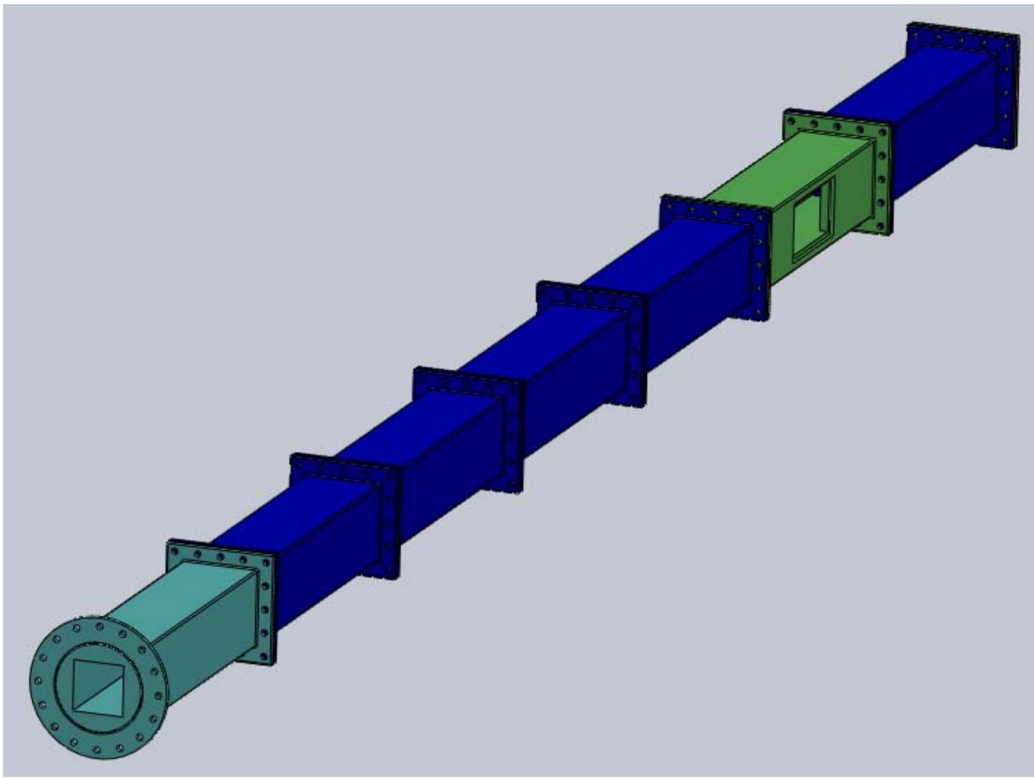

Figure 9. Driven section completely assembled.

Test section

The design of this test section was not completed. During the design of this test section, a new shock tube was commissioned and work was shifted to that tube, specifically the test section as it is readily available.

Diagnostics

In order to properly collect data, gather results, and deduce conclusions, a proper system must be established. An important part of this system is an access window in which the inner portion of the tube can be viewed, particularly the inner two-thirds of the tube away from the sidewalls. This area is less affected by boundary conditions and thus is an excellent location to gather data. Planar Laser Interference Fluorescence,(PLIF), will be one of the two laser diagnostics used. PLIF works by creating a plane of laser light that excites fluorescent particles that have previously been introduced into the flow field. The laser is pulsed at a high frequency and pictures are taken in sync with the frequency of the laser. This particle distribution can be correlated to the density distribution of fluids in the test region. A minimum of two view ports are necessary to use the PLIF diagnostics, one for the laser plane, and one for the camera. Another method employed for visualization is called Particle Image Velocimetry (PIV). Here, as similar to PLIF, the camera essentially takes multiple pictures of particle groups. With multiple pictures of each particle distribution, a computer program is used to create flow fields and velocity profiles. In the case of this project, three view ports will be used in order to gain a 3D representation of the flow field. Before the shock is initiated in the tube, the laser plane and camera must be placed in the correct position depending on the experiment to be run, which is done using appropriate optical settings. To view the position of the laser and camera view interchangeable access windows are needed. The windows should allow the user to view the initial condition section and properly locate the laser plane and camera to obtain the complete view of the fluid interface and also facilitate the laser and camera during shocks. The access widow will be made of transparent material to view the laser plane and the place the camera in the correct location. The pressure window will be made of steel with a small transparent port for diagnostics. The windows will be located on the topside and one of the sides. Also needed for proper data collection are ports to collect pressure and temperature measurements. These can be accommodated by drilling and tapping holes into the test section along the center of the topside of the shock tube.

Support

The shock tube needs a stable base to assemble the modular sections to and also to provide support. Vibrations are observed when the diaphragms rupture and the shock wave propagates down the tube. In order to reduce the affects of those vibrations the tube must be dampened and stiffened. An I-beam was chosen for its availability, cost, and usefulness. It provides adequate stiffness and provides a flat surface for mounting or welding fixtures to. The tube needs to be securely supported to the I-beam, so a mounting bracket was designed to mate the individual modules of the tube to the beam. The brackets are constructed out of the excess pieces of the I-beam and the negative cut outs of the flanges for the modules so as to reduce material costs. Excess I-beam material will be purchased in order to facilitate the bracket construction which should reduce costs overall. The I-beam side of the bracket will be welded to the center of each module. Slightly different brackets are designed for the driver sections to accommodate for the roundness and the need for them to move freely along the axis of the shock tube in order to change the diaphragms. The brackets will attach to the I-beam with a plate and bolts; this will allow the shock tube to be reconfigured for future experiments which will add to the versatility of the tube. The brackets and I-beam are shown in Figure 10.

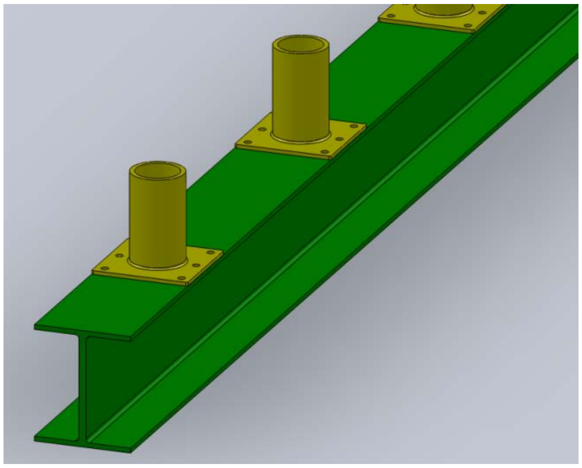

Figure 10. Support I-beam and attachment brackets for driven section.

Angle adjustment

An angle adjustment was needed between 0 and 90 degrees with increments of 5 degrees between 15 and 65 degrees. Several ideas were conceived in attempting to fulfill this need.

Pivot

A pivot point was decided upon to facilitate changing the angular position of the tube. Initially the pivot point was located at the end of the tube, this resulted in excess stresses on the pivot point and it was therefore decided to move the pivot point closer to the tube's center of mass. The pivot system can be seen in Figure 11.

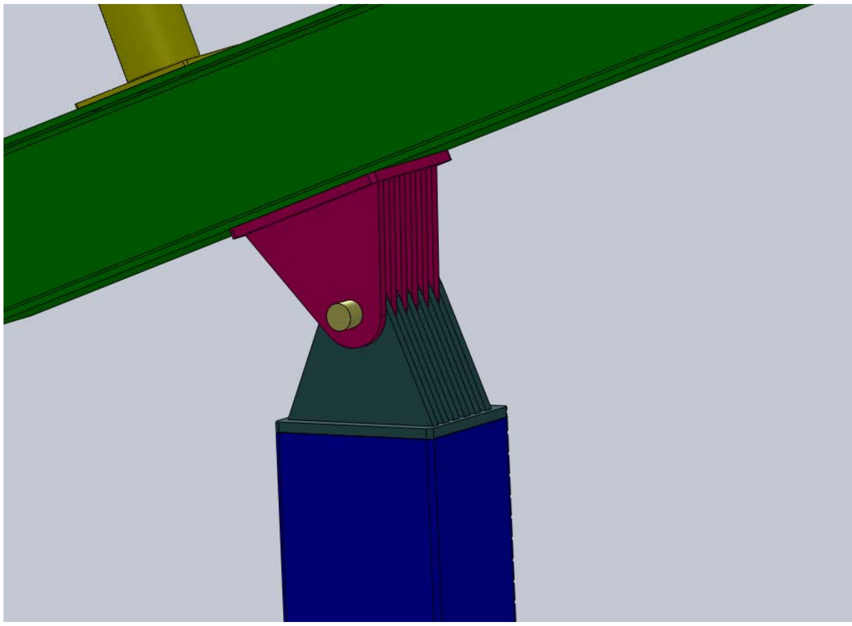

Figure 11. The pivot point located closer to the tube's center of mass.

Movement and support

During movement of the tube, stability, and repeatability are of concern. The tube needs to have the ability to tilt to the same angle between experiments and lock into these positions. The location of the shock tube will be a major influential factor in deciding the final design of the movement device, depending on what the facility can accommodate, such as overhead crane etc. A cable system was suggested with multiple connection points, but was discarded due to unwanted vibrations. A hydraulic piston cylinder system was suggested but the expense of the hydraulic system was deemed undesirable. Ultimately, a system was designed that utilized an overhead sliding crane and a telescoping support system. The telescoping support system allowed rigid support for the shock tube in all configurations between 0 and 90 degrees. Figures 12, 13 and 14 show the shock tube at various inclinations.

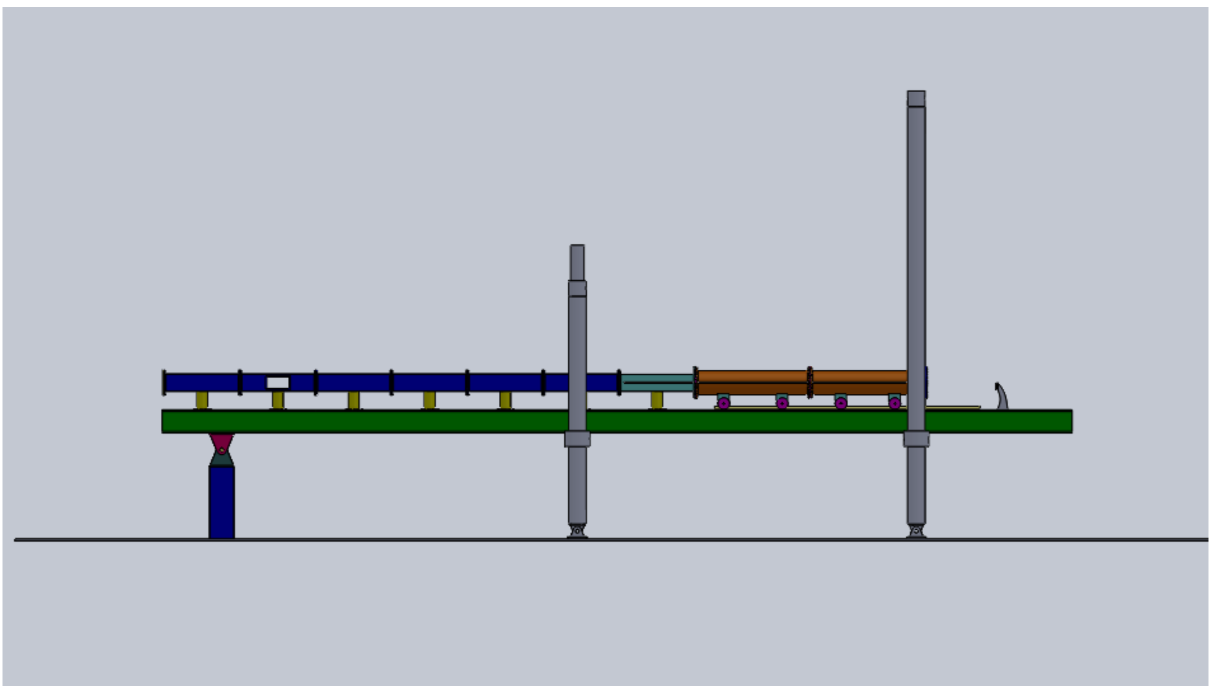

Figure 12. The shock tube in a 0 degree configuration.

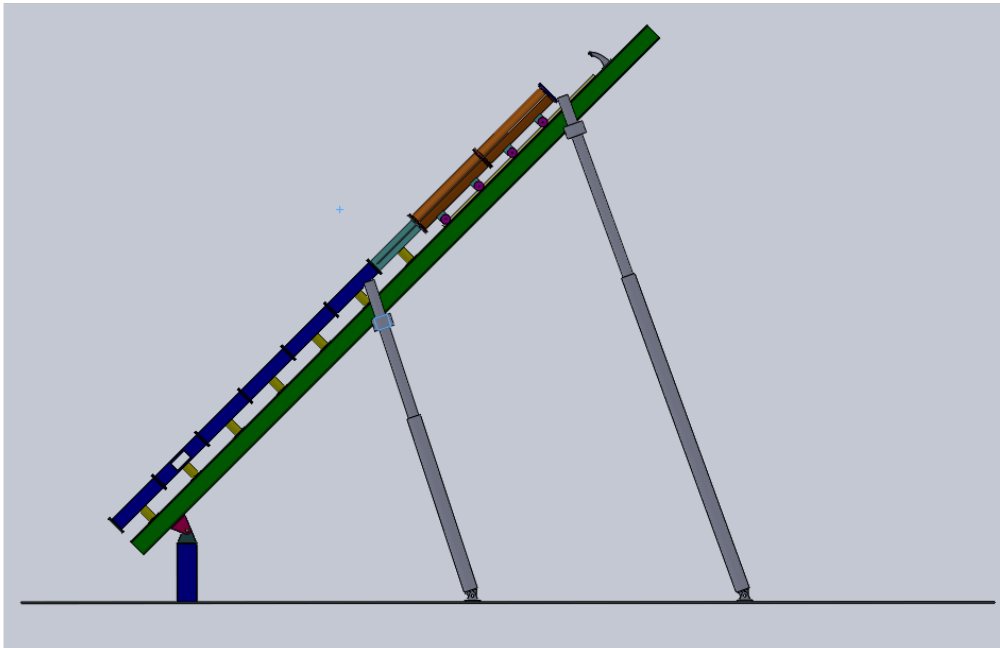

Figure 13. The shock tube in a 45 degree configuration.

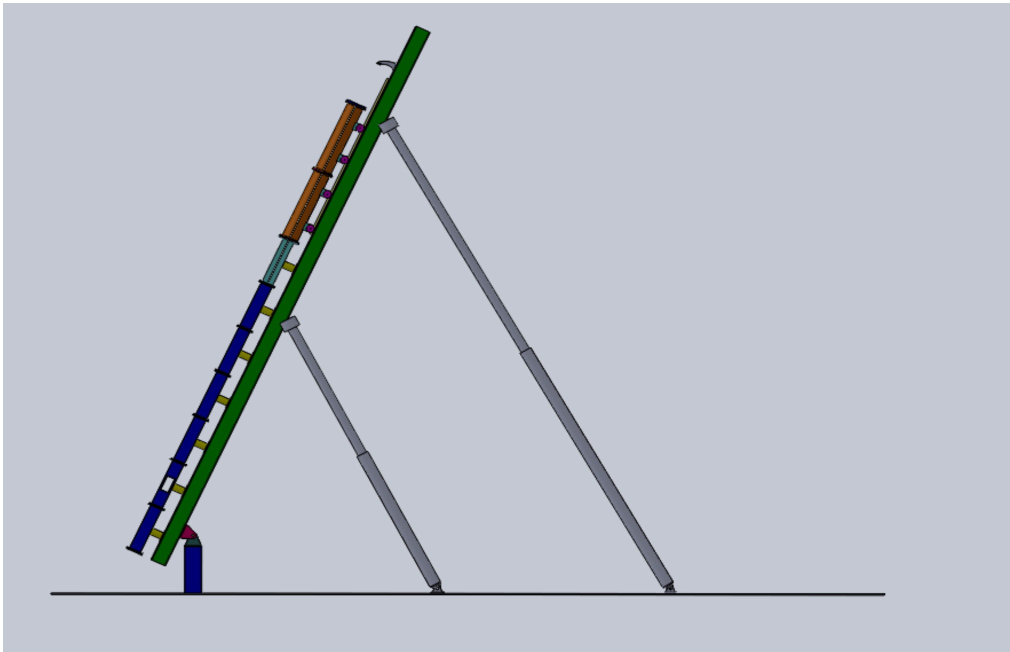

Figure 14. The shock tube in a 65 degree configuration.

This design meets the criterion for small increments between 15 and 65 degrees. After 65 degrees though, such small increments in angle are not possible. A detail of the telescoping support mechanism can be seen in Figure 15.

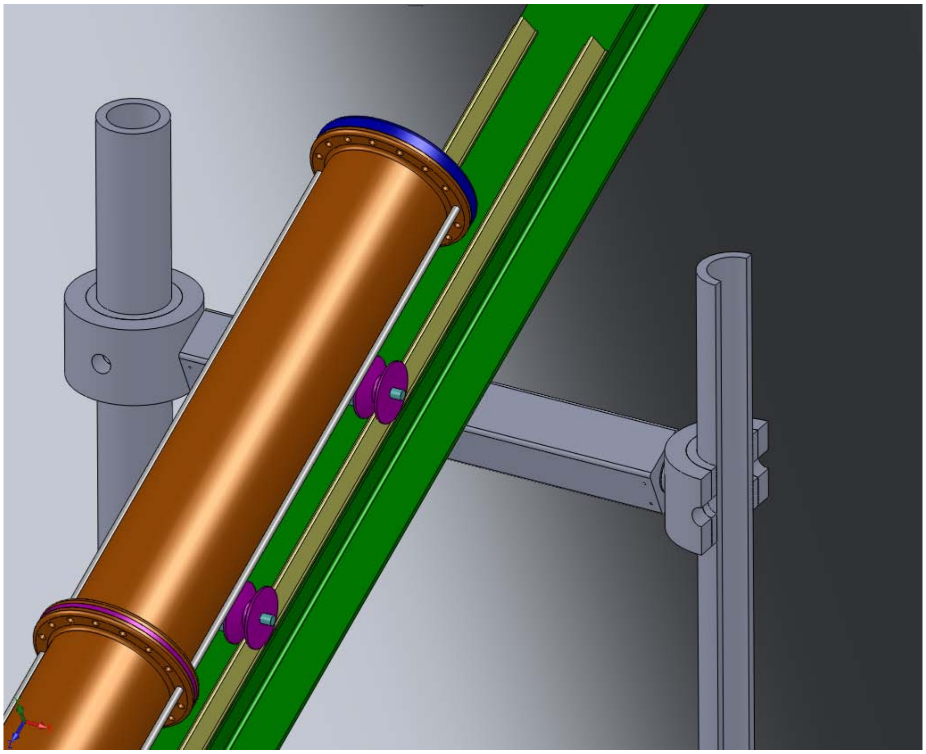

Figure 15. Detail view of the telescoping support system.

When the tube is lifted above 22 degrees, a smaller filler collet is used to hold the tube in place; this piece can be seen in the sectioned view of Figure 15. When the shock tube is in the 90 degree position, the telescoping system is disengaged and the tube will be attached to the overhead crane system and the ground support.

Analysis

To verify that the design of the shock tube was adequate, a stress analysis was completed on the driver. The COSMOS stress analysis program on SolidWorks was used to complete the FEA computations. The main portion that was looked at for the shock tube was the driven sections as the test section was not completely drawn and the driver sections were over designed in their pressure ratings. A internal pressure of 2500 kPa was used to represent the maximum shockwave to be run on the tube. Figure 16 shows the stress analysis results for the driven section.

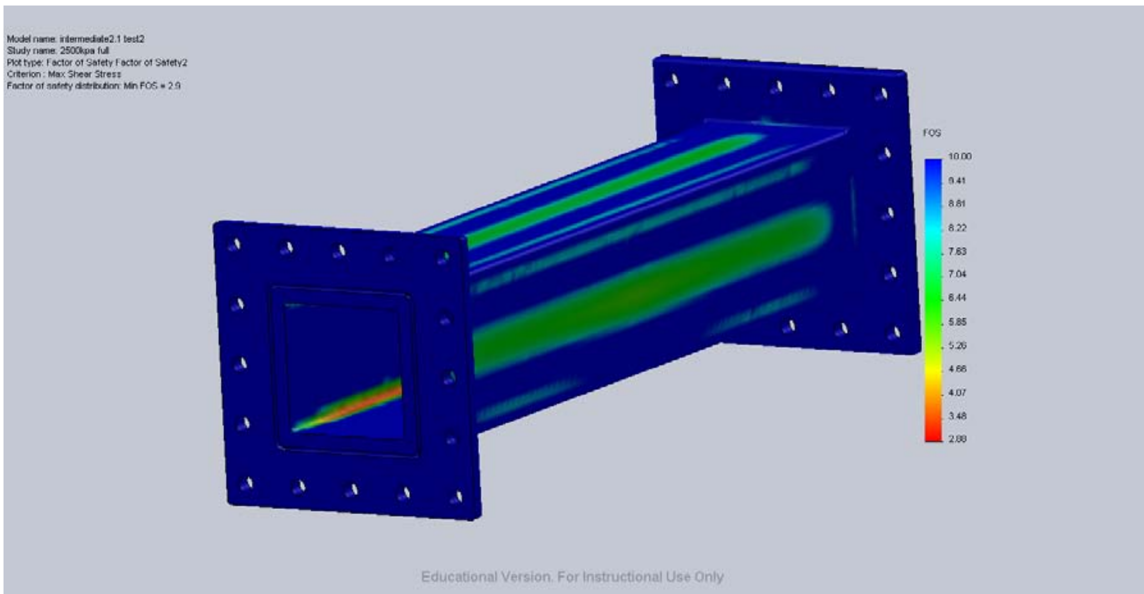

Figure 16. Stress analysis results from COSMOS on the driven section.

Interpreting the results from the FEA analysis, it was seen that a minimum factor of safety for the design was 2.9. The area with the maximum stresses was found at the inner corners of the driven sections. Here there is a stress concentrator, the inside edge, that increased the stress on the section. The material used for this stress analysis was alloy steel, with the sidewalls of the section being 19.05 mm. With this design, this portion of the tube meets the FOS requirements dictated in earlier sections.

CHAPTER IV

SUMMARY

In designing this shock tube, several resources where utilized. These included several papers previously completed by others, SolidWorks® and the internal COSMOS FEA program, the knowledge and brainstorming help from professors and friends, and my own knowledge and experience of design and construction.

The purpose of this paper was to communicate the design process and results for creating a shock tube. There is a need to build a shock tube in order to further study RMI. This particular shock tube had to meet several requirements, as dictated by Dr. Devesh Ranjan, in order to maximize the use of the tube. Maximizing the use includes being able to study a large number of various initial test conditions. The specifications were as follows: dual driver sections, variable inclination, square cross-section, modular construction, 2.5 MPa pressure rating, FOS of 3, diagnostics accessibility, ease of operation, and under $100k. By meeting these requirements, a shock tube capable of studying RMI could be created.

After brainstorming about the design of the shock tube and devising some initial concepts, 3D models where drawn in SolidWorks for better representation and manipulability. Components of the design were initially drawn individually and then placed in an assembly, using this method, components could be modified to accommodate design changes with out having to redraw the entire shock tube. The tube was determined to be 10 m in length with an internal square cross section of 152.4x152.4mm. The shock tube was composed of a driver section, a driven section, a test section, a support system, and an angle adjustment system. The driven section was circular in cross section to maximize the volume and contained the diaphragm holders and diaphragms to initiate the shockwaves. A track and rail system was designed to allow users to efficiently change the diaphragms between experiments. The driven section consists of several 1 m long modules that connect the test section to the driver section. The test section contained the diagnostic system for gathering data and is the location where the initial condition interface is formed. All sections were connected using bolts at the flanges. A support I-beam was used to support the assembled shock tube. To facilitate the inclination of the shock tube, a telescoping angle adjustment mechanism was devised. An overhead crane on a slide rail would be used to lift and lower the end of the tube, changing the angular incline, and two telescoping rods would be used to maintain that position during testing. After performing FEA using COSMOS, it was determined that with an internal pressure of 2.5 MPa, a side wall thickness of 19.05 mm, provided a FOS in the design of 2.9, proving to be an adequate wall thickness. Overall, this design proved robust and efficient, providing the necessary amenities to perform further studies of Richtmyer-Meshkov Instabilities.

REFERENCES

Brouillette, M. (2003). The Richtmyer-Meshkov instability. Annual Review of Fluid Mechanics **34**, 445-468.

Drake, R., Kuranz, C. C., Miles, A. R., Muthsam, H. J. & Plewa, T. 2009. Stellar explosions, instabilities, and turbulence. *Physics of Plasmas* **16**: 041004.

Krivets, V., Long C. C., Jacobs J. W. & Greenough, J. A. 2007. Shock tube experiments and numerical simulation of the single mode three-dimensional Richtmyer-Meshkov instability. Shock Waves **1**: 1205-1210.

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